

GAUGE-INVARIANT MESON PHOTOPRODUCTION WITH EXTENDED NUCLEONS

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The general gauge-invariant photoproduction formalism given by Haberzettl is applied to kaon photoproduction off the nucleon at the tree level, with form factors describing composite nucleons. Numerical results show that this gauge-invariance procedure, when compared to Ohta's, leads to a much improved description of experimental data. Predictions for the new Bonn SAPHIR data for $p(\gamma, K^+)\Lambda$ are given.

1 Formalism

Gauge invariance is one of the central issues in dynamical descriptions of how photons interact with hadronic systems (see Refs.^{1,2}, and references therein). For the simple example of $\gamma p \rightarrow n\pi^+$ with pseudoscalar coupling for the πNN vertex, one finds already at the tree level (see Fig. 1) that the corresponding amplitude violates gauge invariance if the baryon structure is described by form factors.

However, it has been shown in Ref.² that gauge invariance can be restored quite straightforwardly by adding a contact-type interaction current to the usual tree-level s -, u -, and t -channel diagrams (cf. Fig. 1). Indeed, one finds

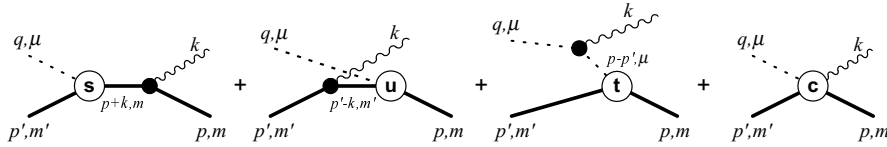


Figure 1: Tree-level photoproduction diagrams. Time proceeds from right to left. The form factors F_s , F_u , and F_t in the text describe the vertices labeled s , u , and t , respectively, with appropriate momenta and masses shown for their legs. The right-most diagram corresponds to the contact-type interaction current required to restore gauge invariance.

that the amplitude then may be written as a linear combination,^{2,3}

$$\varepsilon \cdot \widehat{M}_{fi} = \sum_{j=1}^4 \widehat{A}_j \bar{u}_n (\varepsilon_\mu M_j^\mu) u_p , \quad (1)$$

of individually gauge-invariant currents,

$$M_1^\mu = -\gamma_5 \gamma^\mu k \cdot \gamma , \quad (2)$$

$$M_2^\mu = 2\gamma_5 (p^\mu k \cdot p' - p'^\mu k \cdot p) , \quad (3)$$

$$M_3^\mu = \gamma_5 (\gamma^\mu k \cdot p - p^\mu k \cdot \gamma) , \quad (4)$$

$$M_4^\mu = \gamma_5 (\gamma^\mu k \cdot p' - p'^\mu k \cdot \gamma) , \quad (5)$$

thus providing a manifestly gauge-invariant total current. The coefficient functions,

$$\widehat{A}_1 = \frac{ge}{s-m^2} (1 + \kappa_p) F_s + \frac{ge}{u-m'^2} \kappa_n F_u , \quad (6)$$

$$\widehat{A}_2 = \frac{2ge}{(s-m^2)(t-\mu^2)} \widehat{F} , \quad (7)$$

$$\widehat{A}_3 = \frac{ge}{s-m^2} \frac{\kappa_p}{m} F_s , \quad (8)$$

$$\widehat{A}_4 = \frac{ge}{u-m'^2} \frac{\kappa_n}{m'} F_u , \quad (9)$$

depend on the respective form factors describing the three kinematical situations shown in Fig. 1, i.e.,

$$F_s = F_s(s) = f((p+k)^2, m'^2, \mu^2) , \quad (10)$$

$$F_u = F_u(u) = f(m^2, (p'-k)^2, \mu^2) , \quad (11)$$

$$F_t = F_t(t) = f(m^2, m'^2, (p-p')^2) , \quad (12)$$

where s , u , and t here are the Mandelstam variables. Putting

$$\text{Point-like nucleons: } F_s = F_u = F_t = \widehat{F} = 1 \quad (13)$$

corresponds to the case of structureless, point-like nucleons given by only the first three diagrams of Fig. 1.

As mentioned, for the realistic case of composite nucleons, maintaining gauge-invariance requires the addition of a contact current. This is the origin of the function \widehat{F} appearing here in A_2 . As it turns out,³ there is considerable freedom in choosing \widehat{F} ; in other words, we may use the particular form of \widehat{F} to distinguish between different prescriptions for repairing gauge invariance.

One of the most popular prescriptions of this kind is due to Ohta¹. Using analytic continuation and minimal substitution, Ohta finds that the required \hat{F} is constant,

$$\text{Ohta: } \hat{F} = f(m^2, m'^2, \mu^2) = 1 \quad , \quad (14)$$

determined by the normalization condition for the form factor in the unphysical region where all three legs are on-shell. This corresponds precisely to what one obtains for \hat{F} in the structureless case, Eq. (13), and therefore the purely electric term \hat{A}_2 of Eq. (7) is treated as in the bare case, thus effectively freezing all degrees of freedom arising from the compositeness of the πNN vertex.

The general meson photoproduction theory of Ref.² provides another, more flexible, way of choosing \hat{F} . Haberzettl's formalism allows one to take \hat{F} as a linear combination of all form factors appearing in the problem, i.e.,

$$\text{Haberzettl: } \hat{F} = a_s F_s(s) + a_u F_u(u) + a_t F_t(t) \quad , \quad (15)$$

where the coefficients are restricted by $a_s + a_u + a_t = 1$ in order to provide the proper limit for vanishing photon momentum (see Ref.³ for details).

2 Results

We have tested the relative merits of both prescriptions for repairing gauge invariance for the kaon photoproduction reactions $\gamma p \rightarrow \Lambda K^+$ and $\gamma p \rightarrow \Sigma^0 K^+$. In both cases, one can take over Eqs. (1) and (6)-(9) by replacing the pion by K^+ and the neutron by the respective hyperon.

Using the resonance model of Ref.⁴, one of the main numerical results is summarized in Fig. 2. The upper panel shows χ^2 per data point as a function of one of the leading Born coupling constants, $g_{K\Lambda N}/\sqrt{4\pi}$, for the two different gauge prescriptions by Ohta and Haberzettl ($g_{K\Lambda N}$ was chosen here because χ^2 shows very little sensitivity on the other leading coupling constant, $g_{K\Sigma N}$ ³). Clearly, Haberzettl's method provides χ^2 values better than Ohta's by at least a factor of two, which, moreover, are almost independent of $g_{K\Lambda N}$, in stark contrast to Ohta's. In the fits the form factor cutoff Λ was allowed to vary freely. As is seen in the lower panel of Fig. 2, in the case of Haberzettl's method, the cutoff decreases with increasing $K\Lambda N$ coupling constant, leaving the magnitude of the *effective* coupling, i.e., coupling constant times form factor, roughly constant. Since Ohta's method does not involve form factors for electric contributions [cf. Eqs. (7) and (14)] no such compensation is possible there, and as a consequence the cutoff remains insensitive to the coupling constant (see Ref.³ for more details).

Figure 3 shows differential cross sections for $p(\gamma, K^+)\Lambda$ for four energies for which new Bonn SAPHIR data exist. The numerical results were obtained

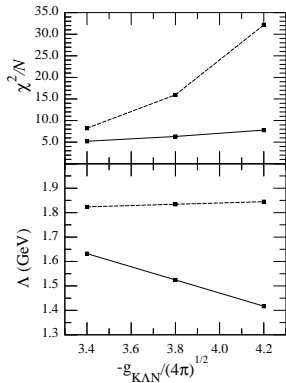


Figure 2: χ^2/N and cutoff parameter Λ as functions of coupling constant $g_{K\Lambda N}$ [solid lines: Eq. (15); dotted lines: Eq. (14)].

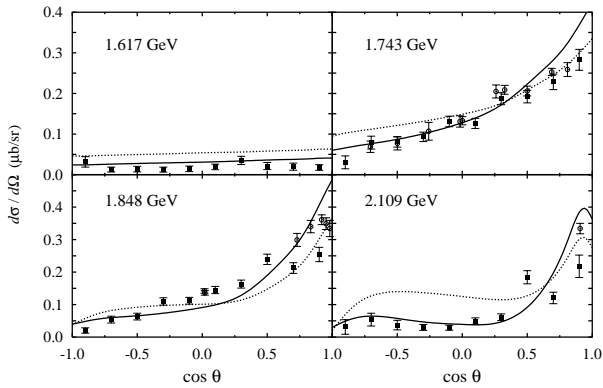


Figure 3: Differential cross sections for $p(\gamma, K^+)\Lambda$ [solid lines: Eq. (15); dashed lines: Eq. (14); experimental points: old SAPHIR data⁶ (open circles); new SAPHIR data⁷ (solid squares)].

within the coupled-channels K -matrix model of Feuster and Mosel⁵. The new data have *not* been included in the fit and the curves shown in Fig. 3 are, therefore, *predictions*. It is evident here that the method put forward by Haberzettl yields results in better agreement with the experimental data.

Our overall conclusion from the present findings is that Ohta's approach seems too restrictive to account for the full hadronic structure while properly maintaining gauge invariance, whereas the method put forward in Ref.² seems well capable of providing this facility. This favorable conclusion regarding Haberzettl's method is corroborated also by the findings of Feuster and Mosel.⁵

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